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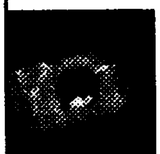
VCSEL APPLICATIONS AND SIMULATION



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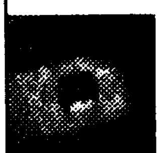
http://www.nas.nasa.gov/Groups/SciTech/sdm/index.html

Outline



INTRODUCTION

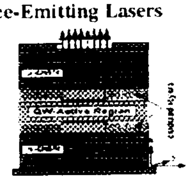
- WHAT IS VCSEL?
- THE VISION

VCSEL is a Semiconductor Laser

- Any laser consists of two ingredients
  - active material
  - cavity
- Semiconductor laser based on electronic transitions involving annihilation of electrons and holes in a semiconductor, e.g. GaAs Gallium Arsenide.
- The first VCSEL is made by Prof. Iga from Tokyo University.
- Focused on native oxide confined GaAs and InGaAs VCSELs, red VCSELs and 1.3 and 1.55 micron wavelength VCSELs.

WHAT IS VCSEL?

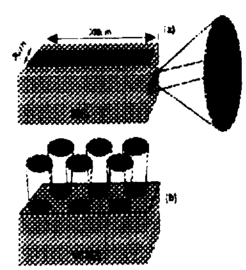
- VCSELs : Vertical-Cavity-Surface-Emitting Lasers
- Vertical-Cavity means that the cavity is vertical to the semiconductor wafer.
- Surface-Emitting means that the light comes out from the surface of the wafer.



- Distributed Bragg Reflectors (DBRs)
  - 20-30 pairs of semiconductor layers
  - reflectivity 0.998
  - layer thickness : $n_1 d_1 = n_2 d_2 = \lambda/4$

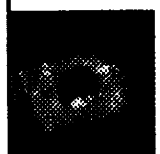
Comparison with Edge-Emitting Laser

- Edge Emitting Diode Laser
  - Light from the edge
  - Astigmatic diverging angle
  - Elliptical beam
- VCSEL
  - Light from the surface
  - smaller divergence angle
  - circular beam cross section



2-D VCSEL Arrays

- **Researches and experiments have been done on VCSEL in recent years.**
- **An ant is looking down at VCSEL array.**
- **One array consists of 400 individual VCSELs.**
- **By A. Scherer, Harnessing the Atom's Light, Scientific American. 1998.**



INTRODUCTION

- **WHAT IS VCSEL?**
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Optoelctronic Integrated Circuit (OEIC)

According to a 1999 marketing study generated by ElectroniCast (Palo Alto, CA), there are four primary OEIC application areas: datacom, telecom, military, and specialty.

The potential OEIC market is projected to be $1.1 billion by FY 2003 and over $5 billion by FY 2008.

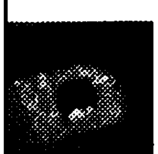
Datacom OEICs are expected to be the most cost effective devices to manufacture because the majority of the components will be serial (single element) devices which operate at 850nm (the λ) in multimode fiber networks.

The Tera-Era Vision

Optoelectronics is the major enabling technology for the tera-era information technology according to the NRC report.

http://www.nap.edu/catalog/5954.html

- **Information Transmission: (Terabit-per-second backbone, long haul networks)**
  - Access network operating at hundreds of gigabits/sec
  - Local area networks operating at tens of gigabits/sec
  - Gigabit per second to the desktop
- **Information Processing: (tera-operations per second computers)**
  - Terabit-per-second throughput switches
  - Multigigahertz clocks
  - Interconnections operating at hundreds of gigabits/sec
- **Information Storage: (Terabyte data bank)**
  - Multiterbyte disk drives
  - Tens-of-gigabyte memory chips



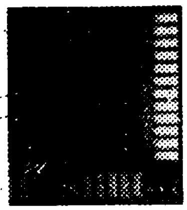
VCSEL APPLICATIONS

- **OPTICAL INTERCONNECTION IN INFORMATION TECHNOLOGY**
- **THE REASON**

Advantages

- **Circular beam**
  - ideal for free space coupling to other optical elements
  - effectively launched into optical fibers
- **Low threshold current (< 1mA)**
- **2-dimensional array capabilities**
- **High Bandwidth under modulation**
  - 1~10 GHz
- **Easily integrated with traditional electronic devices**
  - monolithically (like transistor)
  - heterogeneously by wafer bonding technology with CMOS circuit to form SPA (Smart Pixel Array)

Monolithic Integration to form SPA



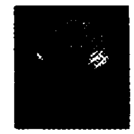
- Monolithic VCSEL/photodetector array
- Photodetectors receive the optical signal from the VCSEL.
- OptiComp Corporation, Nevada

http:// www.dawnbreaker.com/navybriefings/opticomp.html

Another 2-D VCSEL Device

Datacom device:

•2-dimensional array capabilities
•single longitudinal mode optical output
•very small size
•very low threshold current

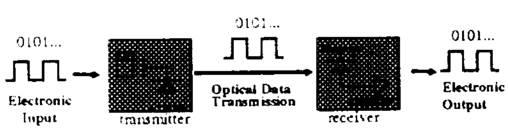


A packaged CSEM VCSEL array with the cap removed. The lasers emit vertically from the chip surface.

Optoelectronics and IT

VCSELs applied to Information Technology:

- Smallest semiconductor laser
- Peta-flop computing with VCSEL-based optical interconnect
- Interprocessor communication
- Multi-gigabit Ethernet



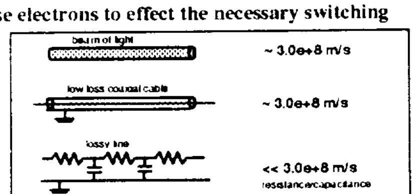
VCSEL APPLICATIONS

- OPTICAL INTERCONNECTION IN INFORMATION TECHNOLOGY
- THE REASON

David Miller : Int J. Optoelectronics Vol. 11, p.155 (1997)

Electrical and Optical Similarities

- Information carried via electromagnetic physics
  signals in wires don't propagate at the electron velocity (10^{5} m/s)
- Like electronic logic devices, optical logic devices use electrons to effect the necessary switching



Electrical and Optical Differences

Very short wavelength
500 nm
electronic 3cm-30m

$\lambda = c/v$

v | vh/e

High carrier frequency
500 THz
electronic 10MHz-10GHz

Large photon energy
2 eV
electronic 40neV-40meV

Implications

- **High frequency**
  - solves difficulty of "high aspect ratio" architectures
  - allows short optical pulses usage
  - allows multiple different frequency carriers
- **Short wavelength**
  - allows free-space multi-channel imaging interconnets
  - allows beamsplitters without back reflection
- **Large photon energy**
  - allows voltage isolation
  - allows quantum impedance conversion

David Miller : Int J. Optoelectronics Vol. 11, pp.155-168 (1997)

"High Aspect Ratio" Architectures

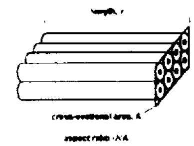
Bits per second ~ $B_0 A/l^2$

$B_0 \sim 10^{15}$ for cables

$B_0 \sim 10^{16}$ for on-chip lines

$B_0 \sim 10^{18}$ for equalized lines

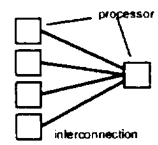
(How can we reach Tb/s ?!)



Architecture

Telecommunication switching

Servers



Note: can exceed the limit by coding, repeating, or multilevel modulation

Note: the above formula is not fundamental

Optical Interconnections

- No aspect-ratio problem
- No modulation-frequency-dependent loss
- Loss in optical fiber is low (0.2dB/km)
- Dispersion is weaker in optical fiber than cable
  - less than 1/10 clock period of dispersion for a 6GHz bandwidth signal over 1km of fiber
- Optical fiber can be small ~125microns in diameter

Short Wavelength

Free-space electrical interconnections are not practical because the wavelength of signal is too long -- longer than a chip. It is hard to focus a wave to a dimension smaller than its wavelength

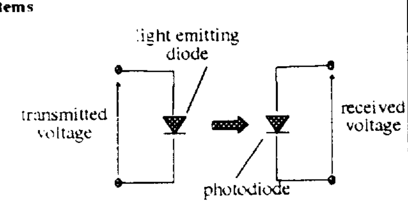
In optics, by contrast, common to image thousands of outputs on one surface to thousands of inputs on another via "free space"; e.g. using lens.

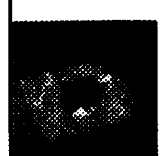
Note: Free space interconnections can be open space or entirely take place within solid or rigid glass structure

Note: Still under research

Voltage Isolation

- **Detection of photon allows us to generate current and voltage but carries no information (or interference) from the d.c. level in the source circuit.**
- **The so-called "opto-isolator" solves an important problem in electrical systems**





VCSEL FORMULATION

Semiconductor Bloch Equations

$$\frac{\partial p_k}{\partial t} = -i\Delta_k p_k - i\Omega_k (n_k^e + n_k^h - 1) + \left.\frac{\partial p_k}{\partial t}\right|_{scat}$$

$$\frac{\partial n_k^\alpha}{\partial t} = -\gamma_n n_k^\alpha + \Lambda_k + \frac{i}{4}(\Omega_k p_k^* - \Omega_k^* p_k) + \left.\frac{\partial n_k}{\partial t}\right|_{c-c} + \left.\frac{\partial n_k}{\partial t}\right|_{c-ph}$$

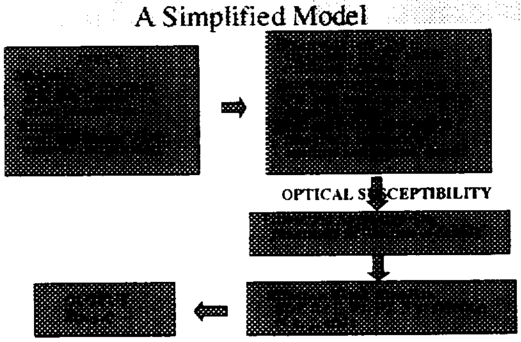
γ_n	carrier recombination rate
Λ_k	electronic pumping
Δ_k	detuning term
Ω_k	Coulomb effect
$c-c$	carrier - carrier scattering
$c-ph$	carrier - phonon scattering

Simplification

$\varepsilon_k^\alpha = \frac{\hbar^2 k^2}{2m_\alpha}$	Carrier Particle Energy
$N^\alpha = \frac{2}{V}\sum_k n_k^\alpha$	Total Carrier Density
$W^\alpha = \frac{2}{V}\sum_k \varepsilon_k^\alpha n_k^\alpha$	Total Energy

- Parabolic energy band
- $N^e = N^h = N$
- n^α_k is described by Fermi-Dirac distribution

Bottom-Up Approach: A Simplified Model



Calculation of Optical Susceptibility

- Solve the Bloch equations for some N to obtain the induced polarization $P(t)$
- Obtain the optical susceptibility $\chi(\omega,N)$ from Fourier Transforms of E and P:

$$P(\omega) = \varepsilon_0 \varepsilon_b \chi(\omega,N)\, E(\omega)$$

- Then refractive index and optical gain follow

$$\chi(\omega,N) = (2/n_b)\delta n(\omega,N) - (i/K)G(\omega,N)$$

- For each value of N, obtain Lorentzian oscillator and background χ_0 to approximate

$$\chi(\omega,N) = \chi_0(N) + A(N)/[i\Lambda(N)+\omega_c+\omega-\delta(N)]$$

Polarization (Material)

The polarization dynamics has a femtosecond time scale, much faster than the dynamics of the electric field and the carrier density, and can often be assumed to adjust instantaneously on the time scale of the latter processes. The polarization can be approximated by $P(t) = P_0(t) + P_1(t)$ where,

$$P_0(t) = \varepsilon_0 n_b^2 \chi_0(N, T_p, T_l) E(t)$$

$$\frac{dP_1}{dt} = \left\{-\Lambda(N, T_p, T_l) + i\left[\omega_c - \frac{\varepsilon_T}{\hbar} - \delta(N, T_p, T_l)\right]\right\} P_1(t)$$

where χ_0, Λ, δ, and A are fitting parameters approximaing

Electric Field Equation

Treat Electric field as a scalar quantity. Within the slowly varying envelope approximation, the time dependence of the electric field (E-field) envelope is governed by

$$\frac{\partial E}{\partial t} = \frac{ic}{2n_b n_g k}\nabla^2 E - \left(\kappa - \frac{\delta n(x,y)\omega_c}{n_g}\right)E + \frac{i\omega_c \Gamma}{2\varepsilon_0 n_b n_g} P$$

n_b , n_g	refractive index : phase, group
$\delta n(x,y)$	derivation of refractive index profile
ω_c	cavity resonance frequency
ε_0	permittivity of vacuum
$\kappa = (c/2Ln_g)\ln(1/r_m)$	$r_m = r_1 r_2$ (reflectivity of 1st and 2nd mirror)
$\Gamma = \beta L_m / L$	L = cavity length, L_m = width of active region
	β = effective coupling constant

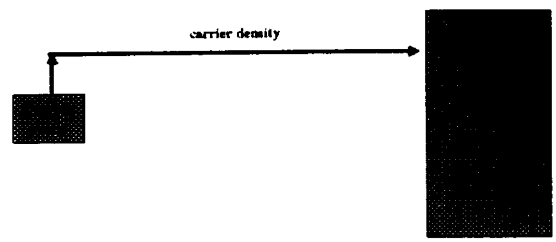
Carrier Density Equation

The dynamics of carrier density is government by the Bloch equation

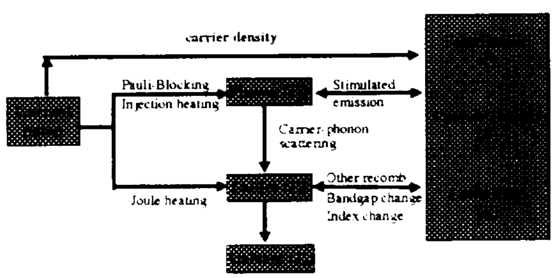
$$\frac{\partial N}{\partial t} = \nabla(D_{NN}(\nabla N) + D_{NT}(\nabla T_p)) - \gamma_n N + \frac{J(x,y)}{e} - \frac{L_m}{4\hbar}\,\mathrm{Im}(P * E)$$

$J(x,y)$	**pumping current profile**
T_p	**plasma temperature**
γ_n	**non-radiative carrier recombination rate**
D_{NN}, D_{TN}	**diffusion coefficients due to N and T_p**
e	**electron charge**
$\hbar = h/2\pi$	**h = plank constant**

Electronic-Optical Couplings



Thermal-Electronic-Optical Couplings



Plasma Temperature

The temperature is derived from the energy (W) equation

$$\left(\frac{\partial W}{\partial T_p}\right)\frac{\partial T_p}{\partial t} = \frac{\partial W}{\partial t} - \frac{\partial W}{\partial N}\frac{\partial N}{\partial t}$$

with $\quad \dfrac{\partial W}{\partial t} = -\nabla J_W - \gamma_T(T_p - T_l) + R_W$

Therefore,

$$\left(\frac{\partial W}{\partial T_p}\right)\frac{\partial T_p}{\partial t} = \nabla(D_{TN}(\nabla N) + D_{TT}(\nabla T_p)) - \gamma_T(T_p - T_l)$$
$$+ (D_{NN}(\nabla N) + D_{NT}(\nabla T_p)) \cdot \nabla\left(\frac{\partial W}{\partial N}\right) + R_W - \frac{\partial W}{\partial N} R_N$$

χ_o

Plasma Temperature (conts.)

where

$$R_W = -\sum_{\alpha, k}\left\{(W^{\alpha} - W_0^{\alpha}) + \frac{m_r}{m_e}\frac{L_m}{4}\,\mathrm{Im}\left[(\omega_k - i\gamma_2) - \frac{\varepsilon_k}{\hbar}\right] P * E - iP * E\right\}$$

$$R_N = -\gamma_n N + \frac{J(x,y)}{e} - \frac{L_m}{4\hbar}\,\mathrm{Im}(P * E)$$

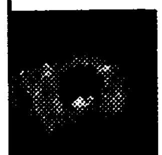
D_{TN}, D_{TT}	**diffusion coefficients due to N and T_p**
γ_T	**plasma cooling rate**
γ_2	**polarization dephasing rate**

The Model

- **Modeling transverse mode dynamics of VCSELs**
- **No assumptions are made about about the type or number of spatial (transverse) modes**
- **Nonlinear carrier density dependence of the optical gain and refractive index**
- **Wavelength dependent dispersion effects on the optical gain and refractive index**
- **The Optical Susceptibility is based on solutions of the semiconductor Bloch equations**
  - includes many-body effects
  - includes device details (qw (w) structure -- InGaAs/GaAs)

Other Methods for VCSEL Simulation

- Select a few transverse modes beforehand and then solve their time evolution (either by ordinary or partial differential equations)
- Solve an eigenvalue problem for the Helmholtz equation, which is uncoupled to the material equations
- Solve time independent, coupled rate equation methods, which contain diffractive terms (in the wave equation) and diffusive transverse terms (in the carrier density equation)



NUMERICAL ALGORITHM

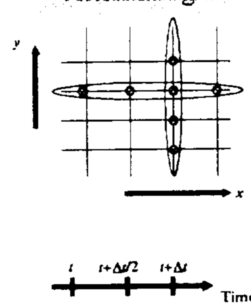
Effective Maxwell Bloch Equations

$$\frac{\partial E}{\partial t} = \frac{ic^2}{2n_g n_b \omega_c}\nabla^2 E - (\kappa - \frac{\delta_n(x,y)\omega_c}{n_g})E + \frac{i\omega_c \Gamma}{2n_g n_b \varepsilon_0} P$$

$$\frac{\partial}{\partial t}\begin{bmatrix} N \\ T_p \end{bmatrix} = C_1 \nabla\left(\begin{bmatrix} D_{NN} & D_{NT} \\ D_{TN} & D_{TT} \end{bmatrix}\nabla\begin{bmatrix} N \\ T_p \end{bmatrix}\right) - C_2\begin{bmatrix} N \\ T_p \end{bmatrix} + \begin{bmatrix} R_1 \\ R_2 \end{bmatrix}$$

$$\left.\begin{aligned} P_0(t) &= \varepsilon_0 n_b^2 \chi_0 E(t) \\ \frac{dP_1}{dt} &= \{-z_1(N)\}P_1(t) - z_2(N)E(t) \end{aligned}\right\} \text{ ODE}$$

Alternating Direction Implicit (ADI)



(1)
- Sweep in x direction
- advance from t to $t+\Delta t/2$
- implicit differences are used for derivative of x.

(2)
- Sweep in y direction
- advance from $t+\Delta t/2$ to $t+\Delta t$
- implicit differences are used for derivative of y.

ADI Illustration

Consider $\partial E = G\nabla^2 E + F$

At the n^{th} time level

$$\frac{E^{(n+1)} - E^{(n)}}{\Delta t} = G(1-f)\nabla_x^2 E^{(n+1)} + Gf\nabla_x^2 E^{(n)}$$

$$\ldots \nabla^2 E^{(n+1)} \ldots \nabla^2 E^{(n)} \ldots E^{(n+1/2)}$$

$$\left[1 - G\Delta t(1-f)(\nabla_x^2 + \nabla_y^2)\right]E^{(n+1)} =$$

$$\ldots \nabla^2 \ldots E^{(n)} \ldots E^{(n+1/2)}$$

ADI Splits

$$\left[1 - G\Delta t(1-f)(\nabla_x^2 + \nabla_y^2)\right]E^{(n+1)} =$$

$$\ldots \nabla^2 \ldots E^{(n)} \ldots E^{(n+1/2)}$$

method	fully implicit	Crank-Nicolson	explicit
f	0	0.5	1

To solve a large system implicitly in both the x and y directions is computationally intensive. As an alternative...

Sweep in x-direction

$$\ldots \nabla^2 E^{(n+1/2)} = \ldots \nabla^2 E^{(n)} \ldots \nabla^2 E^{(n)} \ldots E^{(n+1/2)}$$

Sweep in y-direction

$$\ldots \nabla^2 E^{(n+1)} \quad E^{(n+1/2)} \ldots \nabla^2 E^{(n)}$$

ADI Splits

$$\left[1 - G\Delta t(1-f)(\nabla_x^2 + \nabla_y^2)\right]E^{(n+1)} = \left[1 + G\Delta t f(\nabla_x^2 + \nabla_y^2)\right]E^{(n)} + \Delta t F^{(n+1/2)} + O(\Delta t^2, \Delta x^2, \Delta y^2)\left(\frac{dE}{dt}\right)$$

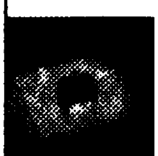
- **Second order accurate in time and space**
- **Solving 2(M-1) sets of (M-1) tridiagonal equations**
- $F^{(n+1/2)}$ **is obtained by Taylor Series**

  $F^{(n+1/2)} = F^{(n)} + \Delta t\ \delta F^{(n)}/\delta t$

Boundary Conditions

- **The above set of equations describe the lasing environment**
- **The approximation of Lorantzian for Polarization is not good for absorption**
- **At the region where N is small (10^{12} 1/m^3)**
  - $J = 0$
  - $W = 2k_g\Gamma_r N$
  - $E = P = 0$

  Simplified Γ_p and N equations

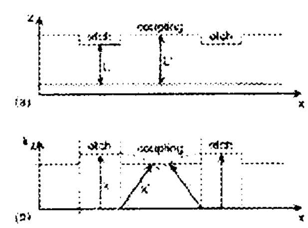


COMPUTATION RESULTS

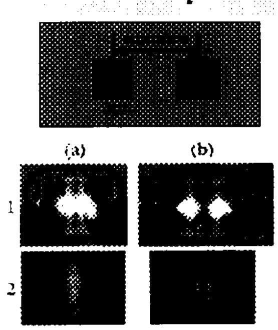
The Experiment

Two-element phased array of antiguided vertical-cavity lasers by D. K. Serkland, et. al.
Applied Physics Letters , Vol. 75, No. 24, Dec., 1999.

- **2 adjacent VCSELs**
- **High optical index between the 2 VCSELs**
- **Emitted light are coupled and VCSELs interfered to each other**

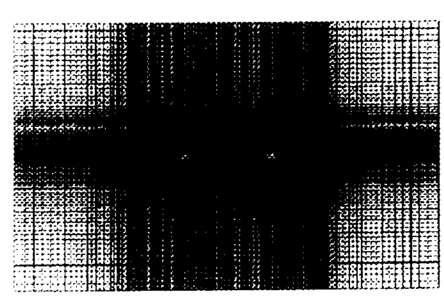


Experimental Results

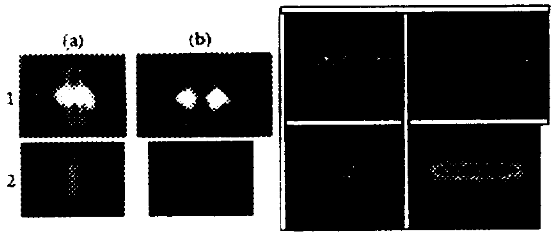


- **near-field (1) and far-field (2) images**
- **8 (a) and 20 (b) microns separations**
- **The far field**
  - peak at the center for the 8-micron separation
  - no peak at the center for the 20-micron separation.

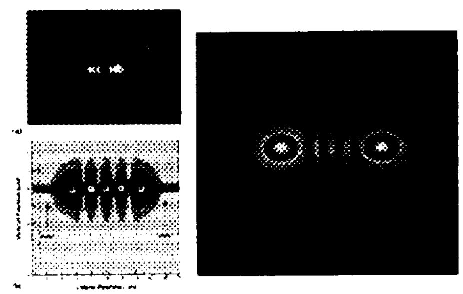
The Computational Grid



Computational Results

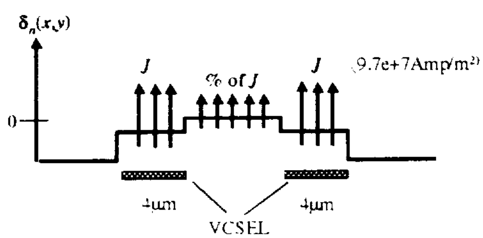


Near-Field Solution

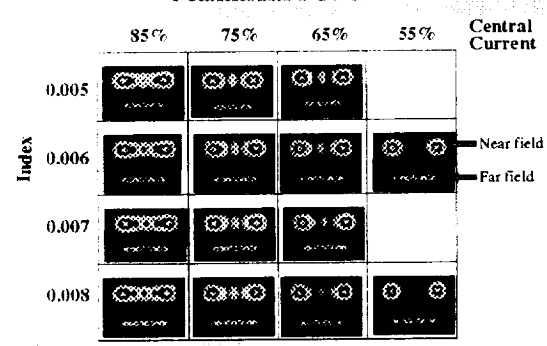


Guiding Index and Central Current

When do we have phase-locking (resonance)?
When do we have maximum intensity output?



Maximum Power



Conclusion

- **Changing Index**
  - affects on the far-field pattern
  - for Index=0.006, no phase-locking, results are time averaged, transition stage from 3 spots to 4 spots
  - increase the index, increase the pattern at the inner edge of the VCSEL
- **Changing Central Current**
  - affects on the near-field pattern
  - 85% of *J* alone doesn't create lasing environment
  - Increase the current, increase the intensity
  - Increase the current, increase the interference at the center